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CALIBRATION OF KNOLLENBERG FSSP LIGHT—SCATTERING COUNTERS FOR MEASUREMENT OF CLOUD DROPLETS

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By

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US Army Electronics Research and Development Command
Atmospheric Sciences Laboratory
White Sands Missile Range, NM 88002

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It is well known that atmospheric fog degrades the performance of DOD electro-optic sensors. A quantitative assessment of these effects generally requires knowledge of droplet size distributions, which can have considerable spacial and temporal variations. An attractive approach to measuring fog (or cloud) drop sizes is the use of light-scattering counters. In this paper we evaluate the response characteristics of the Knollenberg model FSSP-100 light-scattering counter, which is well-suited for measurement of particles as large

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20. ABSTRACT (cont)

as fog droplets. This instrument has been widely used throughout DOD for aerosol measurement, without adequate understanding of its response characteristics. In this paper we find that measurement of cloud drop size distributions using the manufacturer's calibration can lead to artificial bumps or knees in the distributions at about 0.6μm, and sometimes at 2μm to 4μm radius. These artifacts are a consequence of the instrument having multivalued or slowly changing response in these regions of particle size. We have developed a modified calibration procedure that removes these artifacts, so that the true droplet size distribution can be obtained. We also have found that measurement of slightly nonspherical particles with refractive indexes characteristic of those of atmospheric aerosols will generally lead to under-sizing if the FSSP manufacturer-supplied calibration is used, but likely by not more than a factor 2.

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INTRODUCTION

A number of investigators have used[1 2 3 4 5] or are presently using (several papers in the proceedings of the 8th International Cloud Physics Conference, Clermont-Ferrand, France, 15-19 July 1980) the Knollenberg Forward Scattering Spectrometer Probe (FSSP) to determine the drop size distribution or liquid water content in atmospheric cloud. (This device is manufactured by Particle Measurement Systems, Boulder, Colorado.) As droplets flow through an illuminated volume within the device, laser-light scattered by a single drop into a particular near-forward solid angle is measured and used to determine droplet size by electronically classifying response pulses according to their magnitude. Determination of drop size from the response is indirect because of the dependence of the response on factors other than particle size, namely, the refractive index of the drop and the lens geometry of the counter optical system.

In the previously reported studies the manufacturer-supplied calibration was used to determine the drop size (and by integrating the drop size, liquid water content) from the instrument response voltages. We show in this paper that this procedure can result in the drop size spectrum displaying artificial peaks that are peculiar to the instrument, and we offer a calibration procedure (slightly different than that supplied by the manufacturer) that removes these instrumental artifacts. Our calibration procedure, which has been described for the similar Knollenberg CSASP-100 counter in an earlier paper,[6] involves grouping size channels so that regions of multivalued responses are avoided. As a result, the size resolution of the instrument is somewhat

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[1]Stephens, G. L., G. W. Paltridge, and C. M. R. Platt, "Radiation Profiles in Extended Water Clouds. III: Observations," J Atmos Sci, 35:2133-2141, 1978.

[2]Heymsfield, A. J., C. A. Knight, and J. E. Dye, "Ice Initiation in Unmixed Updraft Cores in Northeast Colorado Cumulus Congestus Clouds," J Atmos Sci, 36:2216-2229, 1979.

[3]Low, R. D. H., L. D. Duncan, and Y. Y. Roger R. Hsiao, Microphysical and Optical Properties of California Coastal Fogs at Fort Ord, ASL-TR-0034, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1979.

[4]Low, R. D. H., Fog Evolution in the Visible and Infrared Spectral Regions and its Meaning in Optical Modeling, ASL-TR-0046, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1979.

[5]Duncan, L. D., and R. D. H. Low, Bimodal Size Distributions Models for Fogs at Meppen, Germany, ASL-TR-0056, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1980.

[6]Pinnick, R. G., and H. J. Auvermann, "Response Characteristics of Knollenberg Light-Scattering Aerosol Counters," J Aerosol Sci, 10:55-74, 1979.

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reduced (as compared to that inferred from the manufacturer-supplied calibration), particularly for droplets in the 0.5μm to 4μm radius range. For larger particles our calibration differs little from the manufacturer's, in agreement with the findings of Cannon and Grotewold.[7]

Our calibration is based on Mie calculations of the instrument's response (to water drops). These calculations have been experimentally verified for various kinds of uniform particles. In section 2, this verification is discussed. In section 3, data collected with an FSSP in atmospheric fog is reduced to drop size distribution in two ways: using the manufacturer's calibration and using our Mie calibration. Differences are greatest in the 0.5μm to 2μm radius range, where particles are comparable in size to the wavelength of the FSSP (He-Ne) laser source. In section 4, calibration of the FSSP instrument for measurement of spherical particles other than water droplets is discussed. In section 5, some results and comments are offered on measurement of slightly irregular particles. Finally, in section 6, FSSP sampling losses are investigated.

FSSP RESPONSE CALCULATIONS

Our conjecture is that the FSSP response can be calculated assuming plane wave scattering by a sphere; that is, by assuming the well-known Mie theory. Of course, these calculations must take into account the particle size and refractive index, the wavelength of the FSSP laser source, and the geometry of the instrument optics. Although such calculations are straightforward and have been reported previously,[6] appendix A addresses some minor complications that are caused by focusing of the laser source and have not been considered before.

To check the validity of the response calculations, we measured the FSSP response to uniform particles of known size and refractive index: spherical particles of polystyrene, polyvinyltoluene and styrene divinylbenzene latex, glass beads, and aluminum. The results are summarized in figure 1, where the theoretical response is expressed in cross-section per particle and the measured response in volts per particle. The experimental scale has been normalized to the theoretical scale to achieve best agreement between experiment and theory for the latex particles. The resulting normalization factor (C = 2.8×10^6 V cm^{-2} was used for the remaining experimental data.

It is clearly evident in figure 1 that the theoretical response for the FSSP is corroborated by measurements of uniform particles having three markedly

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[7]Cannon, T. W., and W. W. Grotewold, "Improved Drop Generators for Calibration of Drop Spectrometers and Use in Laboratory Cloud Physics Experiments," J Appl Meteorol, 19:901-905, 1980.

[6]Pinnick, R. G., and H. J. Auvermann, "Response Characteristics of Knollenberg Light-Scattering Aerosol Counters," J Aerosol Sci, 10:55-74, 1979.

different indexes of refraction and having radii 1μm to 20μm. In particular, note that the second latex resonance around 1μm radius (where a number of latex particle sizes are available) is borne out well by the measurements. Further, similar measurements on uniform latex particles with a different FSSP instrument agree with these results (S. G. Jennings, private communication, 1980). Thus, the theoretical response calculations adequately predict the FSSP response for spheres, regardless of effects caused by multimode operation of the instrument laser source that might invalidate the plane wave assumption in Mie theory.

When making cloud or fog measurements with the FSSP, we should therefore rely on the theoretical response curve for water particles shown in figure 2, rather than the manufacturer-suggested calibration, which is also shown in the figure, for comparison. (Appendix B explains how the manufacturer's calibration is plotted in figure 2.) A word of caution is required concerning use of the theoretical curve to redefine size channels. Channels should be grouped with less size resolution than the response curve dictates because, in practice, spectra broadening effects result in some cross-channel sensitivity. Thus, channels set near regions of multivalued response and narrow size channels, where the response curve is steep, should be avoided.

A comparison of the manufacturer's calibration and our calibration, which takes into account the theoretical response curve for water and the spectra broadening considerations, is presented in table 1. We caution the reader that our calibration shown in table 1 can only be used for FSSP instruments with discriminator levels set as they are for our particular instrument. FSSP instruments with different discriminator level settings would of course require different channel groupings and size definitions (see appendix B).

FSSP FOG MEASUREMENTS

To demonstrate the difference between invoking the manufacturer's calibration and our Mie calibration for some real data, we chose some fog measurements made during February and April, 1978, near Meppen, Germany. The measurements were made with an aspirated FSSP operated 2 m above ground level in a range-cycling mode allowing maximum use of the dynamic range of the instrument. In this mode droplets in four overlapping size ranges are measured sequentially, and we have combined the data for a 5-min time interval into a single size distribution. Actually, the instrument completed a cycle of measurements in only 50 s, but we chose to integrate over a longer period because the fog was relatively stable and we wanted to reduce statistical counting errors.

The drop size distributions obtained from these measurements are displayed in figure 3; the dashed curve derives from the manufacturer's calibration, and the solid curve from our Mie calibration. (In both distributions the data from the first channel [of range 3] has been ignored because it was suspect.) Numerous other size distribution comparisons are given in appendix C. We note that the distribution derived from our calibration has fewer size channels, which results from the fact that we cannot use pulse height discriminator levels set in regions of multivalued response--such channels must be

grouped together to avoid these regions. In fact, we suggest that the peaks around 0.6µm and 2µm radius which appear in the distribution derived from the manufacturer's calibration are a consequence of particle pile-up in channels where the response is multivalued or slowly changing. Thus, the overall shape of the distribution derived from the manufacturer's calibration is correct, but it contains artificial humps, knees and points of inflection near sizes where the Mie response function oscillates. These artifacts can only be expected to appear if the instrument is properly aligned and calibrated; otherwise, the Mie resonances may not be resolvable. Additionally, the artifacts will likely not appear for haze aerosol unless the particles are homogeneous and spherical.

The fact that the drop size distributions derived from the manufacturer's calibration in the 10µm to 15µm region show a more pronounced peak is the result of the slightly different character of the response curves in this region (see figure 2).

Finally, we note that the liquid water contents for the distributions in figure 3 differ by only 16 percent (the Mie calibration resulting in lower liquid content), suggesting the manufacturer's calibration is adequate for liquid water content determinations in cloud and fog. The differences in extinction coefficients calculated from these distributions are also small; we found the extinction coefficient to be 28 percent lower for the Mie calibration at a wavelength λ = 0.55µm, 26 percent lower at λ = 4µm, and 16 percent lower at λ = 10µm. Comparisons of liquid water content and extinction coefficients for a wide range of fog measurements, contained in appendix D, show similar differences.

FSSP MEASUREMENTS OF OTHER SPHERICAL PARTICLES

Measurement of particles other than fog or cloud with the FSSP requires a different calibration. If the particles are homogeneous spheres, then the calibration can easily be worked out from the response curves (by grouping channels together to avoid regions of multivalued response) in much the same way as for water. Examples of response curves for several refractive indexes characteristic of atmospheric aerosol constituents are shown in figure 4. As is evident from the figure, the positions of the resonances are refractive index-dependent. The manufacturer's calibration very roughly approximates the general form of these response curves, except for absorptive particles with radii greater than 3µm.

To demonstrate our calibration procedure for homogeneous particles with refractive index m = 1.45-0i we measured in the laboratory an aerosol of Dow Corning 200 fluid. The resulting size distributions inferred from the data appear in figure 5. For this aerosol the artifacts in the distribution derived from the manufacturer's calibration move to slightly smaller particle sizes (as compared to fog, figure 3), since the oscillations in the response functions are shifted (compare the theoretical response curves for m = 1.33-0i and m = 1.45-0i in figures 2 and 4). We have not made independent measurements of the Dow oil drop size distribution, so this figure by itself does not prove that our calibration procedure is more valid than that supplied by the

manufacturer. However, it is unlikely that our technique of aerosol generation (a nebulizer) would result in the bimodal distribution of droplets that results from invoking the manufacturer's calibration.

In cases where the FSSP is used to measure aerosol of unknown or mixed composition (and refractive index), we suggest that the manufacturer's calibration be used, with corrections for error in particle size determined by an envelope encompassing the possible response curves. Under the constraint that no large ($\gtrsim$ 3μm radius) absorptive particles are present, these errors can be expected to be on the order of a factor 2 or less.

FSSP MEASUREMENTS OF IRREGULAR PARTICLES

The FSSP calibration for irregular particles is not so clear-cut as it is for spheres. One problem is that the intensity of light scattered by a nonspherical particle depends on its orientation with respect to the laser beam direction, so that even identical nonspherical particles measured with the FSSP may result in markedly different response pulses. This will obviously degrade the size resolution of the instrument. There is also the complication of deciding what equivalent radius to assign to irregular particles which might have rather complex morphology--such particles commonly occur in the atmosphere.

We decided to make only a superficial investigation of the FSSP response to irregular particles by limiting our measurements to only slightly nonspherical pollens and spores. Figure 6 shows micrographs of some of these particles, which include puff ball spores, paper mulberry, ragweed, lycopodium, sweet vernal, and pecan pollens. The measured response to these particles, shown compared to the calculated response for spheres of equal cross section, are presented in figure 7. Also shown for comparison is the FSSP manufacturer's calibration. The comparison suggests that the FSSP responds to slightly nonspherical particles very nearly as it would to spheres of equal cross section and refractive index. We can also conclude that application of the manufacturer's calibration to measurements of slightly nonspherical atmospheric aerosols (which generally have refractive indexes close to that of pollens and spores) will lead to undersizing of the particles, but probably by not more than a factor 2. (We realize of course that the manufacturer did not intend that his calibration be used for atmospheric aerosols.)

Our speculation regarding the FSSP response to ice particles (which have refractive index 1.30-0i) is that if the particles are only slightly irregular (like the pollen particles of figure 6) their response can be approximated by that of water spheres. However, it is doubtful that their response characteristics would evidence resonance structure. Therefore, we cannot recommend our calibration procedure over that supplied by the manufacturer in this case.

FSSP SAMPLING LOSSES

In its normal configuration the FSSP is aircraft-mounted. However, it can be purchased with an aspirator and horn for ground or laboratory use. Since the FSSP is capable of sensing particles that have appreciable fall speeds, the question of nonisokinetic sampling losses was investigated. To accomplish this, a mixture of relatively small (7μm mean diameter) puff ball spores and rather large (40μm mean diameter) glass beads were sprinkled into the ambient air within about 5 cm of the FSSP horn. (The aspirator fan draws air through the horn and FSSP inlet [which has minimum diameter 1.9 cm] at a rate of 0.5 l s^{-2} The proportion of spores to beads measured by the FSSP (for either vertical or horizontal horn orientations) was in good agreement (within 50 percent) with that determined by counting the number of spores and beads in the mixture sprinkled onto a microscope slide. It should be mentioned that there is considerable uncertainty in determining the proportion of spores to beads in both FSSP and microscope measurements because a significant fraction of the spores stick to the larger beads. In any case, assuming that the 7μm spores are sampled with 100 percent efficiency under calm air conditions (which is a reasonable assumption), these results suggest a similar efficiency for the larger beads (and cloud droplets at least 40μm in diameter).

CONCLUSION

In summary, utilization of the FSSP manufacturer-supplied calibration will lead to fairly accurate values of cloud or fog liquid water content, but the true cloud or fog drop size distributions will be distorted. These distortions are evident in the form of bumps or knees in the size distribution at about 0.6μm and 2μm radii and are a consequence of the instrument having multivalued or slowly varying response in these regions of particle size. We have offered an alternative calibration procedure that removes these artifacts in the drop size distribution. This calibration procedure can be applied with slight modification to FSSP measurements of polydispersions of particles other than water, providing they are spherical and uniform in composition. For measurement of slightly irregular particles or particles of mixed composition, the manufacturer's calibration will generally lead to under-sizing of particles, but likely by not more than a factor 2.

TABLE 1. PARTICLE SIZE CHANNEL WIDTHS (RADII IN MICROMETERS) FOR THE KNOLLENBERG FSSP LIGHT SCATTERING AEROSOL COUNTER*

	Instrument Range							
	0		1		2		3	
Channel	a	b	a	b	a	b	a	b
1	1.0-2.5	-	1.0-2.0	-	0.5-1.0	0.5	0.25-0.5	-
2	2.5-4.0	-	2.0-3.0	1.4	1.0-1.5	1.4	0.50-0.75	0.5
3	4.0-5.5	3.2 - 5.4	3.0-4.0	3.1	1.5-2.0	1.4	0.75-1.0	
4	5.5-7.0	5.4	4.0-5.0	3.1	2.0-2.5		1.00-1.25	
5	7.0-8.5	7.6	5.0-6.0	5.8	2.5-3.0		1.25-1.5	
6	8.5-10	7.6	6.0-7.0	5.8	3.0-3.5		1.50-1.75	1.4
7	10-11.5	10.7	7.0-8.0	7.1	3.5-4.0	3.3	1.75-2.0	1.4
8	11.5-13	10.7	8.0-9.0	7.1	4.0-4.5	3.3	2.00-2.25	
9	13-14.5	14.2	9.0-10	8.7	4.5-5.0	5.1	2.25-2.5	
10	14.5-16	14.2	10-11	8.7	5.0-5.5	5.1	2.50-2.75	
11	16-17.5	18.0	11-12	11.3	5.5-6.0		2.75-3.0	
12	17.5-19	18.0	12-13	11.3	6.0-6.5	6.4	3.00-3.25	2.5
13	19-20.5	21.4	13-14	13.5	6.5-7.0	6.4	3.25-3.5	2.5
14	20.5-22	21.4	14-15	13.5	7.0-7.5		3.5-3.75	
15	22-23.5	24.6	15-16	16.2	7.5-8.0	7.5	3.75-4.0	3.6

*(a) As specified by PMS
(b) Present work, under the assumption particles are water droplets

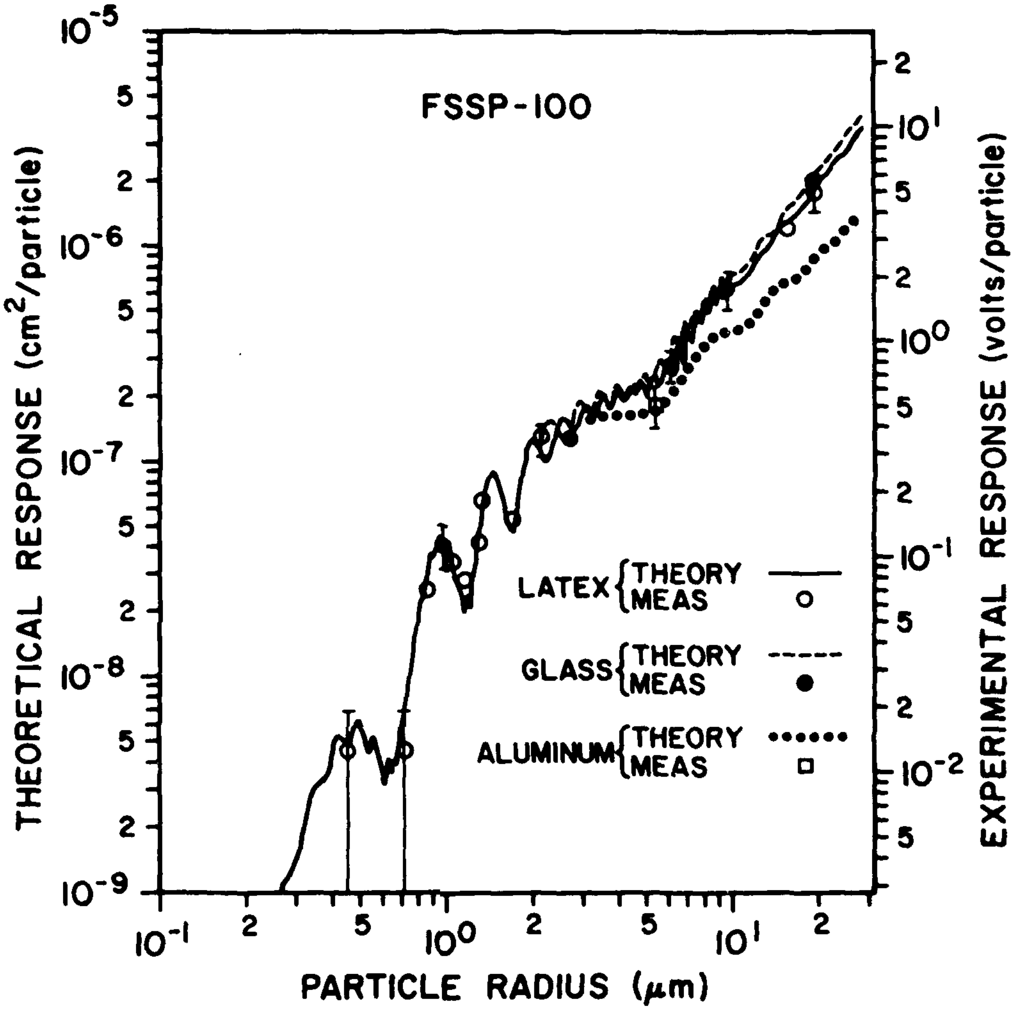

Figure 1. Comparison of the Knollenberg FSSP response: measured for latex spheres with refractive index m = 1.588-0i (open circles), glass beads with m = 1.51-0i (closed circles), and aluminum spheres with m = 1.44-3.69i (square); and calculated using Mie scattering theory (smooth curves). The latex particles used include particle diameters 0.945μm, 1.48μm, 1.74μm, 32.2μm, 40μm polystyrene; 2.02μm, 2.154μm, 2.35μm polyvinyltoluene; and 2.70μm, 2.77μm, 3.44μm, 4.33μm styrene divinylbenzene. The theoretical curves for glass beads and aluminum only extend down to about 3μm radius.

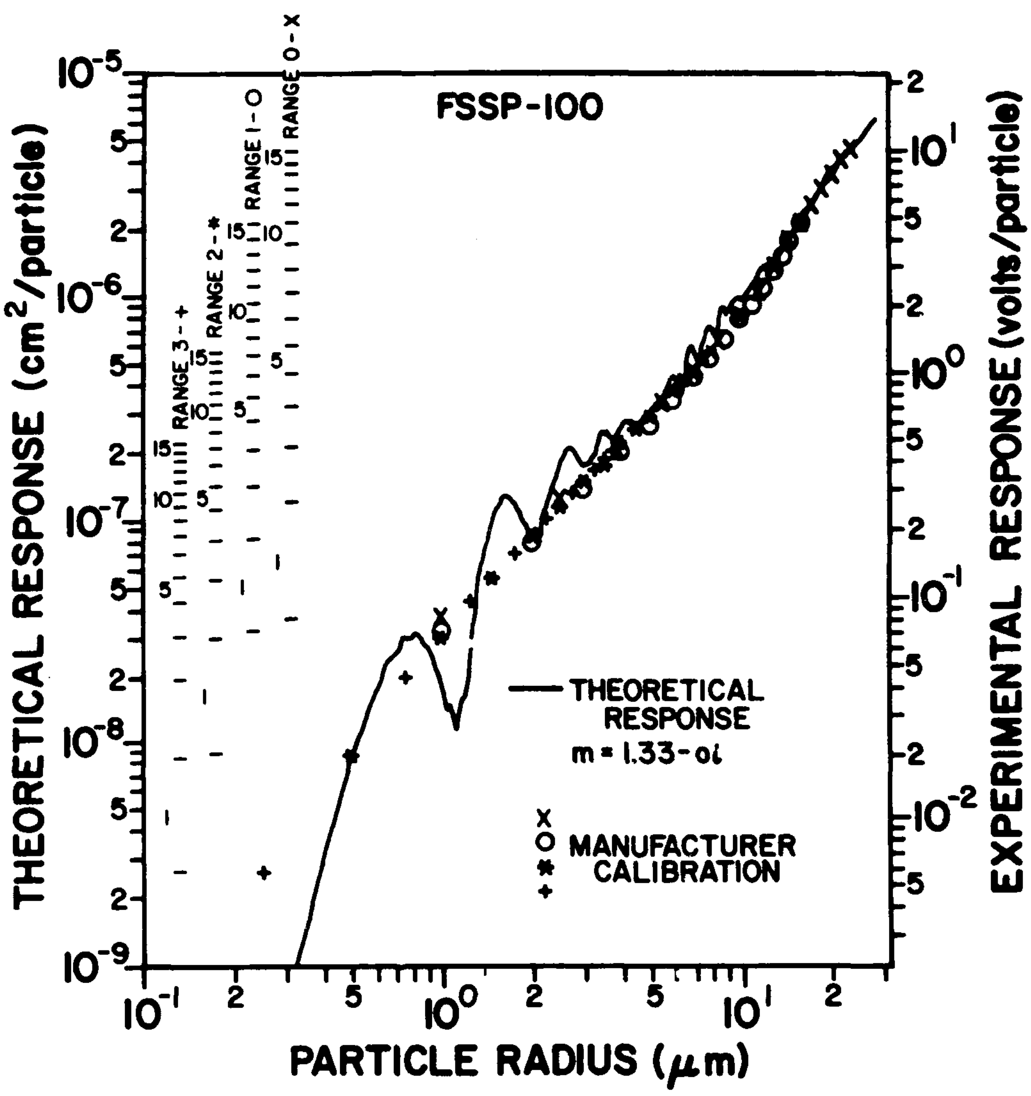

Figure 2. Relation between the FSSP response and water drop size as predicted by theory (smooth curve), and as advertised by the manufacturer (points). The pulse height discriminator level settings (for ranges 0, 1, 2, and 3) used in this particular instrument are also shown.

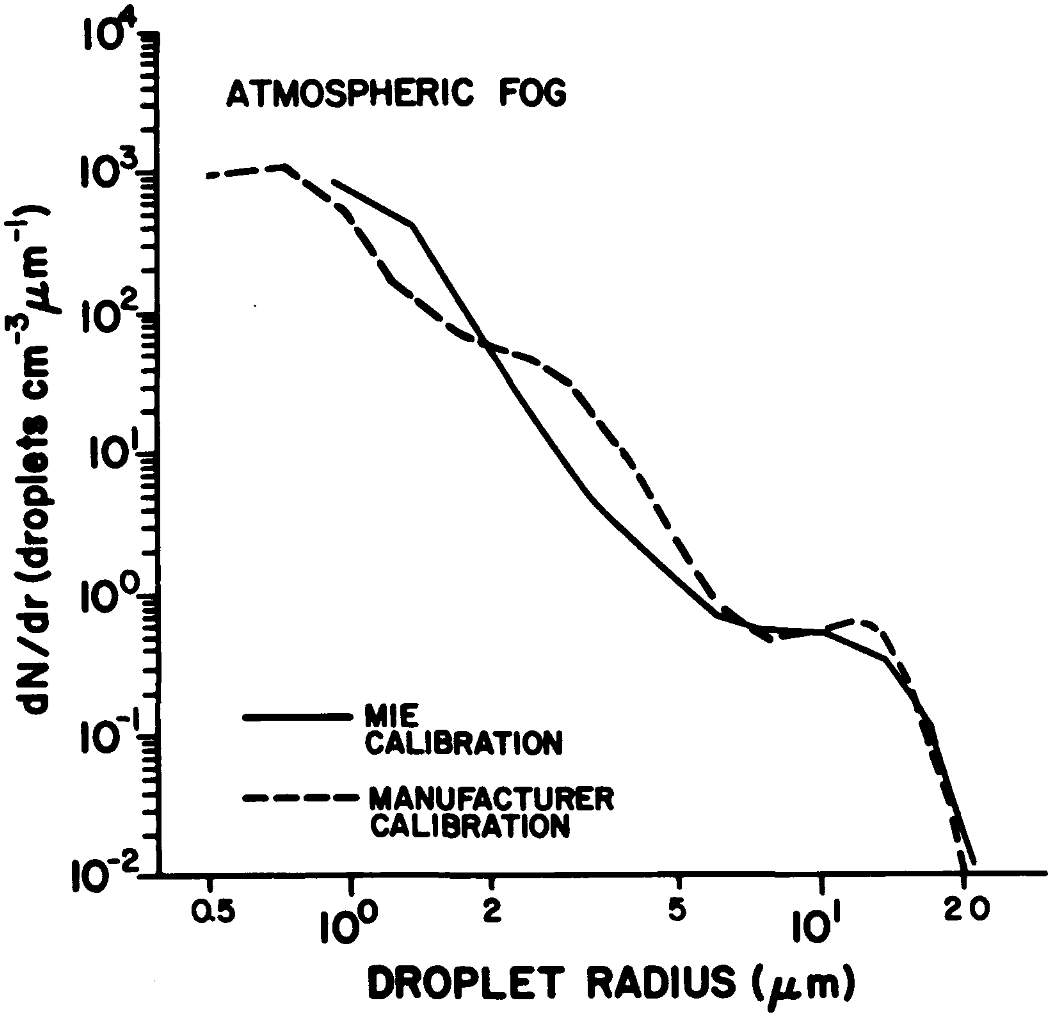

Figure 3. Comparison of FSSP fog drop size distributions obtained in two ways: one using the manufacturer-supplied calibration (dashed curve) and the other using our suggested calibration based on the theoretical response curve of figure 2 (solid curve). The peaks that appear around 0.6μm and 2μm radius in the dashed-curve distribution are believed to be artifacts caused by multivalued response characteristics of the FSSP instrument.

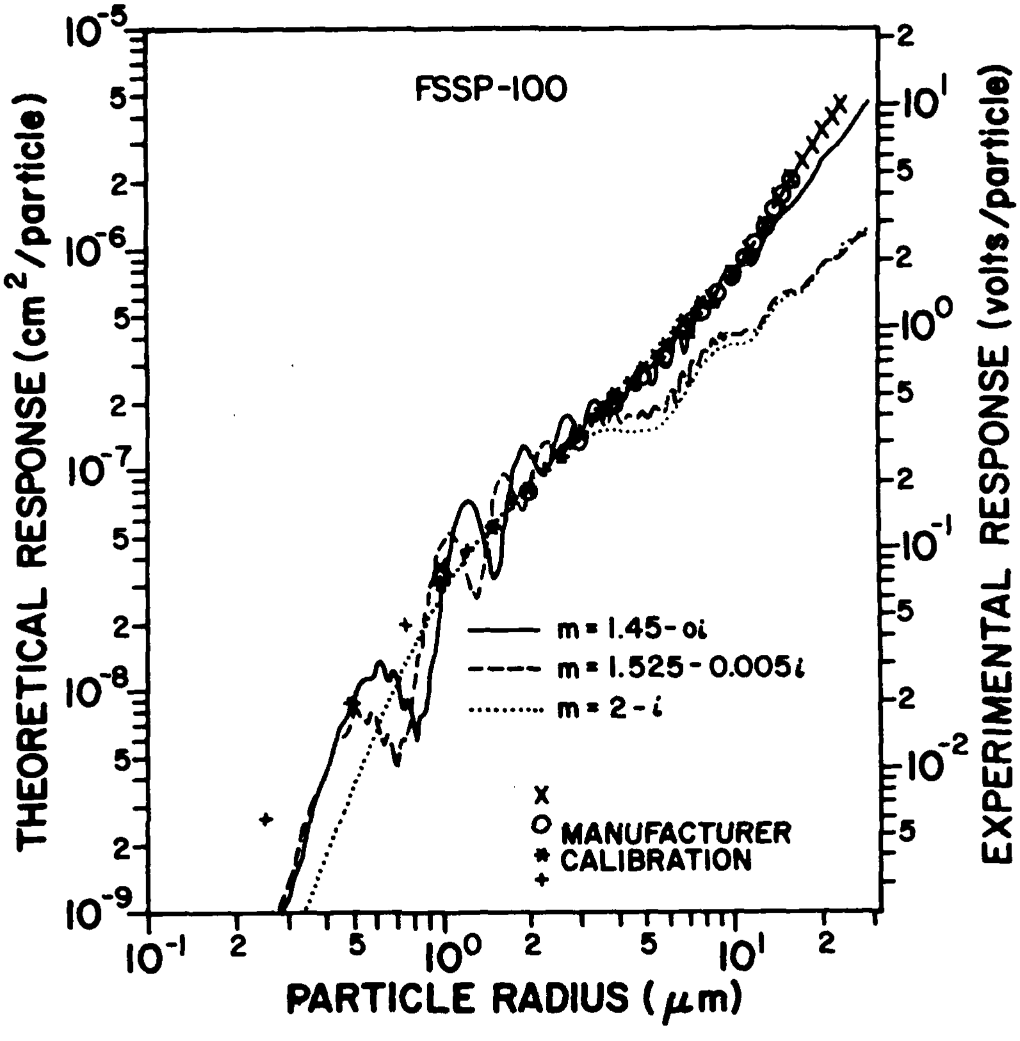

Figure 4. FSSP response curves for particles with refractive indexes characteristic of those of atmospheric constituents: soil-derived aerosols with m = 1.525-0.005i,[8] desert aerosols with m = 1.45-0i,[9] and carbonaceous aerosol with m = 2-i. The manufacturer-supplied calibration relating instrument response to particle size is shown for comparison.

[8]Grams, G. W., I. H. Blifford, Jr., D. A. Gillette, and P. B. Russell, "Complex Index of Refraction of Airborne Soil Particles," J Appl Meteorol, 13:459-471, 1974.

[9]Reagan, J. A., D. M. Byrne, M. D. King, J. D. Spinhirne, and B. M. Herman, "Determination of the Complex Refractive Index and Size Distribution of Atmospheric Particulates From Bistatic-Monostatic Lidar and Solar Radiometer Measurements," J Geophys Res, 85:1591-1599, 1980.

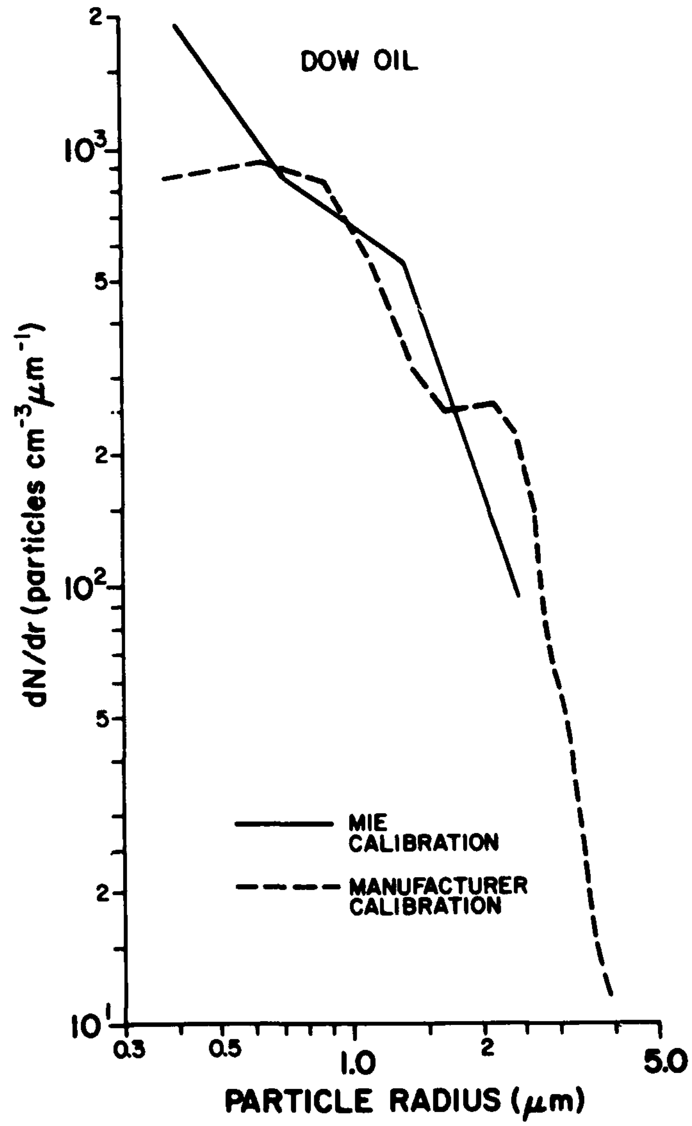

Figure 5. Same as figure 3, except in this case oil droplets (with m = 1.45-0i) were measured rather than fog. The bumps in the size distribution derived from the manufacturer-supplied calibration (dashed curve) again are believed to be artifacts caused by multivalued response characteristics of the FSSP. The bumps are shifted to slightly smaller sizes (as compared to fog) in accordance with the shift in the positions of the oscillations in the response curve.

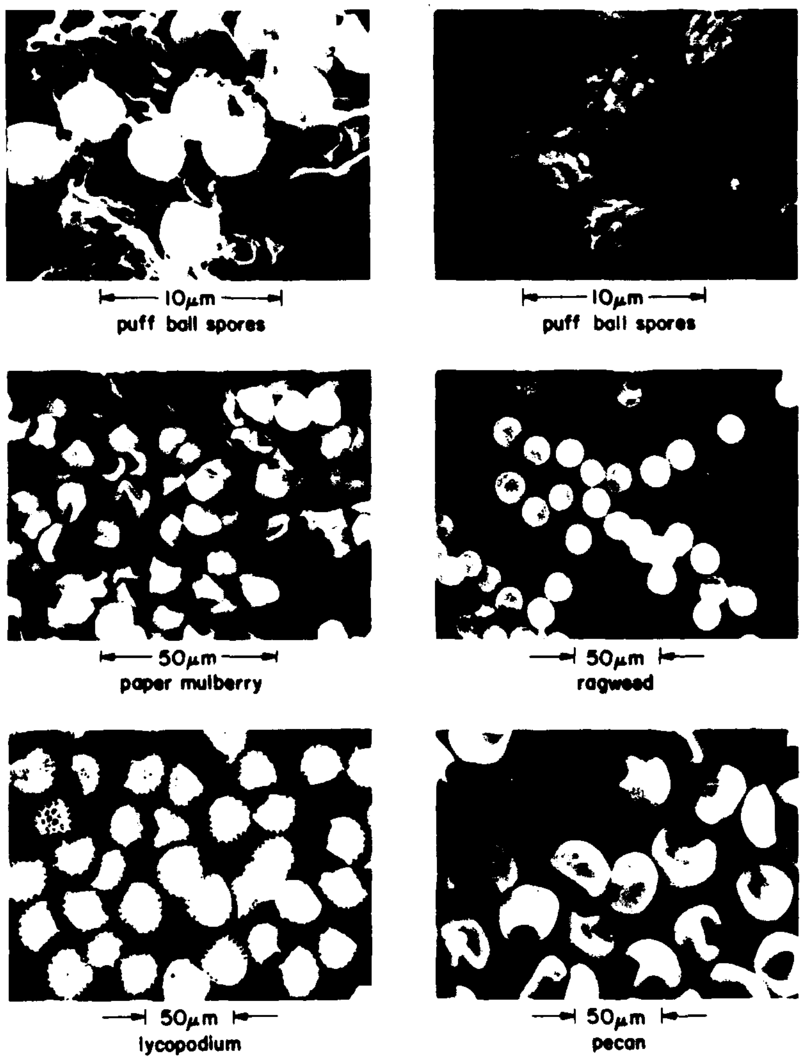

Figure 6. Scanning electron microscope micrographs of slightly nonspherical pollens and spores used to measure the FSSP response characteristics.

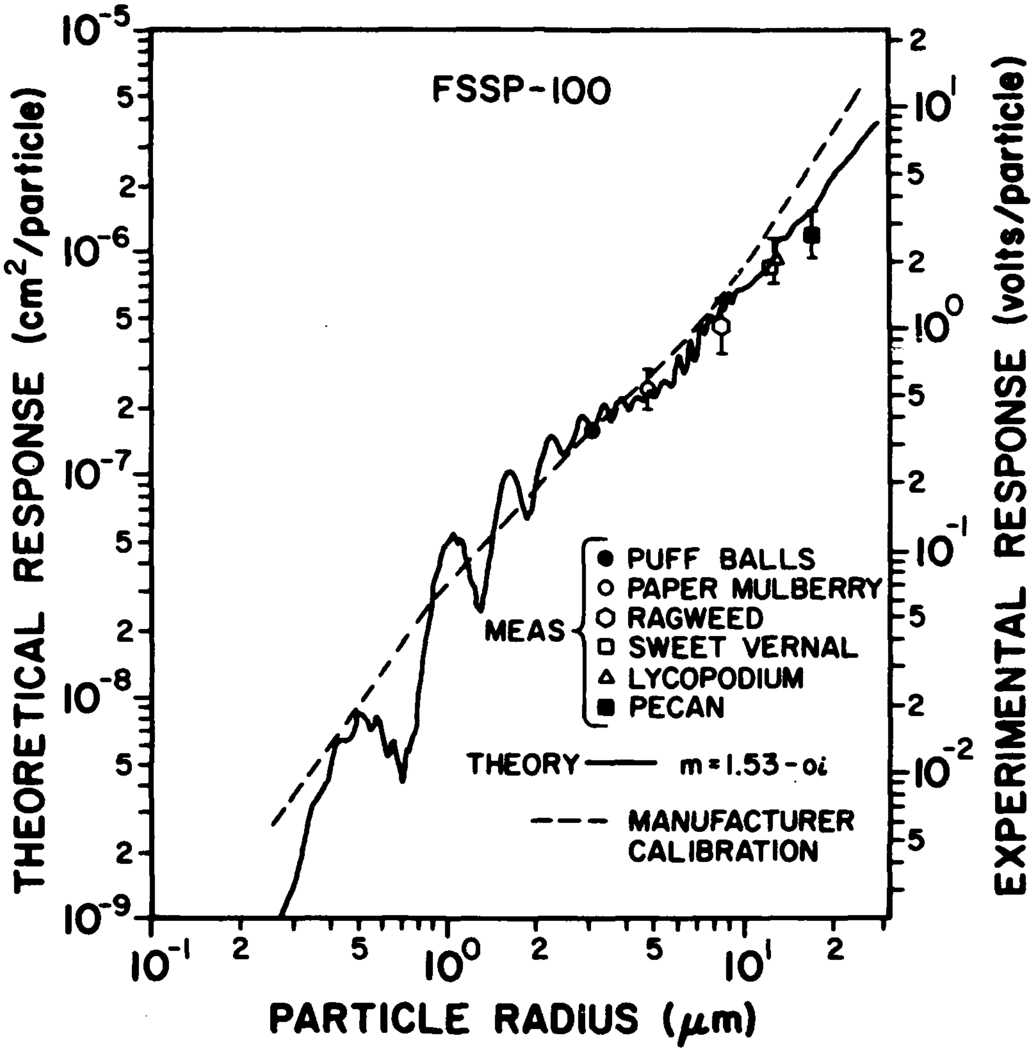

Figure 7. Measurements of the FSSP response to slightly nonspherical pollen and spore particles (some of which are shown in figure 6). The measurements are compared to the theoretical response for spheres of equal cross section (smooth curve) and to the manufacturer-supplied calibration (dashed curve).

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3. Low, R. D. H., L. D. Duncan, and Y. Y. Roger R. Hsiao, Microphysical and Optical Properties of California Coastal Fogs at Fort Ord, ASL-TR-0034, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1979.

4. Low, R. D. H., Fog Evolution in the Visible and Infrared Spectral Regions and its Meaning in Optical Modeling, ASL-TR-0046, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1979.

5. Duncan, L. D., and R. D. H. Low, Bimodal Size Distributions Models for Fogs at Meppen, Germany, ASL-TR-0056, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1980.

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7. Cannon, T. W., and W. W. Grotewold, "Improved Drop Generators for Calibration of Drop Spectrometers and Use in Laboratory Cloud Physics Experiments," J Appl Meteorol, 19:901-905, 1980.

8. Grams, G. W., I. H. Blifford, Jr., D. A. Gillette, and P. B. Russell, "Complex Index of Refraction of Airborne Soil Particles," J Appl Meteorol, 13:459-471, 1974.

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APPENDIX A

FSSP RESPONSE FOR VARIOUS COLLECTING ANGLES

The solid angle over which scattered light is detected in the FSSP depends on the size of the dump spot located on the right angle prism and the dimension of the prism itself (see figure A-1). According to the manufacturer, the dump spot has a radius of 2 mm and light is collected out to a radius of 8.7 mm on the prism face. Since the prism face is 38 mm away from the particle plane, the limits of the solid angle over which light is detected are easily calculated: $\alpha = \arctan\left(\frac{2}{38}\right) \approx 3°$, $\beta = \arctan\left(\frac{8.7}{38}\right) \approx 13°$. These are the values used by Pinnick and Auvermann.[1]

Because it is likely that these dimensions are not identical on every instrument, and because it is possible that for some instruments the laser beam may not be accurately centered on the dump spot, sensitivity calculations were made to determine the effects on the calculated response curve for small changes in α and β. Thus, response curves for water ($m = 1.33-0i$) were determined for the angle pairs $\alpha = 2.5°$, $\beta = 14°$; $\alpha = 3°$, $\beta = 14°$; and $\alpha = 3.5°$, $\beta = 14°$ (see figure A-2). It was found that increasing β by 1° results in a negligible change in the calculated response curve, but that changing α by 0.5° affects the response curve markedly. As α decreases from 3.5° to 2.5°, the response of the instrument is significantly enhanced for particles with radii greater than ~ 2µm and the "knee" in the response curve moves from ~ 3.5µm to ~ 7µm. These effects can be attributed to the forward "diffraction" lobe. For intermediate-sized particles the lobe becomes more sharply peaked in the forward direction, so that an appreciable fraction of the scattered light will be found between 2.5° and 3.5°. For larger particles the lobe becomes even more sharply peaked and the fraction of scattered light between 2.5° and 3.5°, while still appreciable, is reduced.

An additional factor not taken into account in calculating the FSSP response curves is the focusing of the incident laser light. Using an analytical expression derived by Hodkinson and Greenfield,[2] Cooke and Kerker[3] have considered this effect for various optical counters in which the light is highly focused. Their formulation is based on the assumption that the light is

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[1]Pinnick, R. G., and H. J. Auvermann, "Response Characteristics of Knollenberg Light-Scattering Aerosol Counters," J Aerosol Sci, 10:55-74, 1979.

[2]Hodkinson, J. R., and J. R. Greenfield, "Response Calculations for Light-Scattering Aerosol Counters and Photometers," Appl Opt, 4:1463-1474, 1965.

[3]Cooke, D. D., and Milton Kerker, "Response Calculations for Light-Scattering Aerosol Particle Counters," Appl Opt, 14:734-739, 1975.

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focused to a dimension that is large compared to the sizes of the particles, but sufficiently small that a photon passing the particle plane is equally likely to have "originated" from any point on the focusing lens. In the FSSP the light is focused to a diameter of ~ 200μm at the particle plane. The half-angle of the focusing cone can be calculated as follows: $\sigma/2 = \arctan\left(\frac{1.5}{60}\right) \approx 1.4°$, where the diameter of the laser beam at the condensing lens is 3 mm and the focal length of the condensing lens is 60 mm. The FSSP response curve for water, calculated using the expressions of Cooke and Kerker and normalized to unit intensity at the particle plane, generally falls between the curves for $\alpha = 2.5°$, $\beta = 14°$, and $\alpha = 3°$, $\beta = 14°$ in figure A-2. (It is closer to the latter curve.) The effect of the converging beam is thus to spread the detecting solid angle beyond the lower and upper limits of α and β.

The curve for $\alpha = 2.5°$ and $\beta = 14°$ probably places an upper bound on the actual response curve of the instrument. In this work the values $\alpha = 3°$ and $\beta = 14°$ have been used in calculating response curves for various refractive indexes. The curves do not differ in any significant way from those presented by Pinnick and Auvermann.[1]

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[1]Pinnick, R. G., and H. J. Auvermann, "Response Characteristics of Knollenberg Light-Scattering Aerosol Counters," J Aerosol Sci, 10:55-74, 1979.

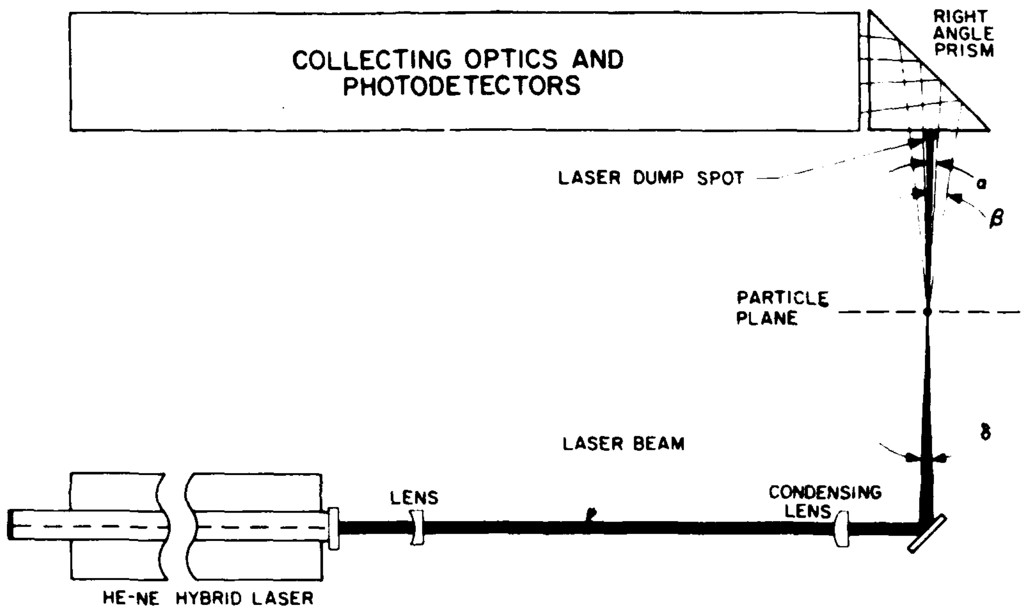

Figure A-1. Schematic of the FSSP-100 optical system.

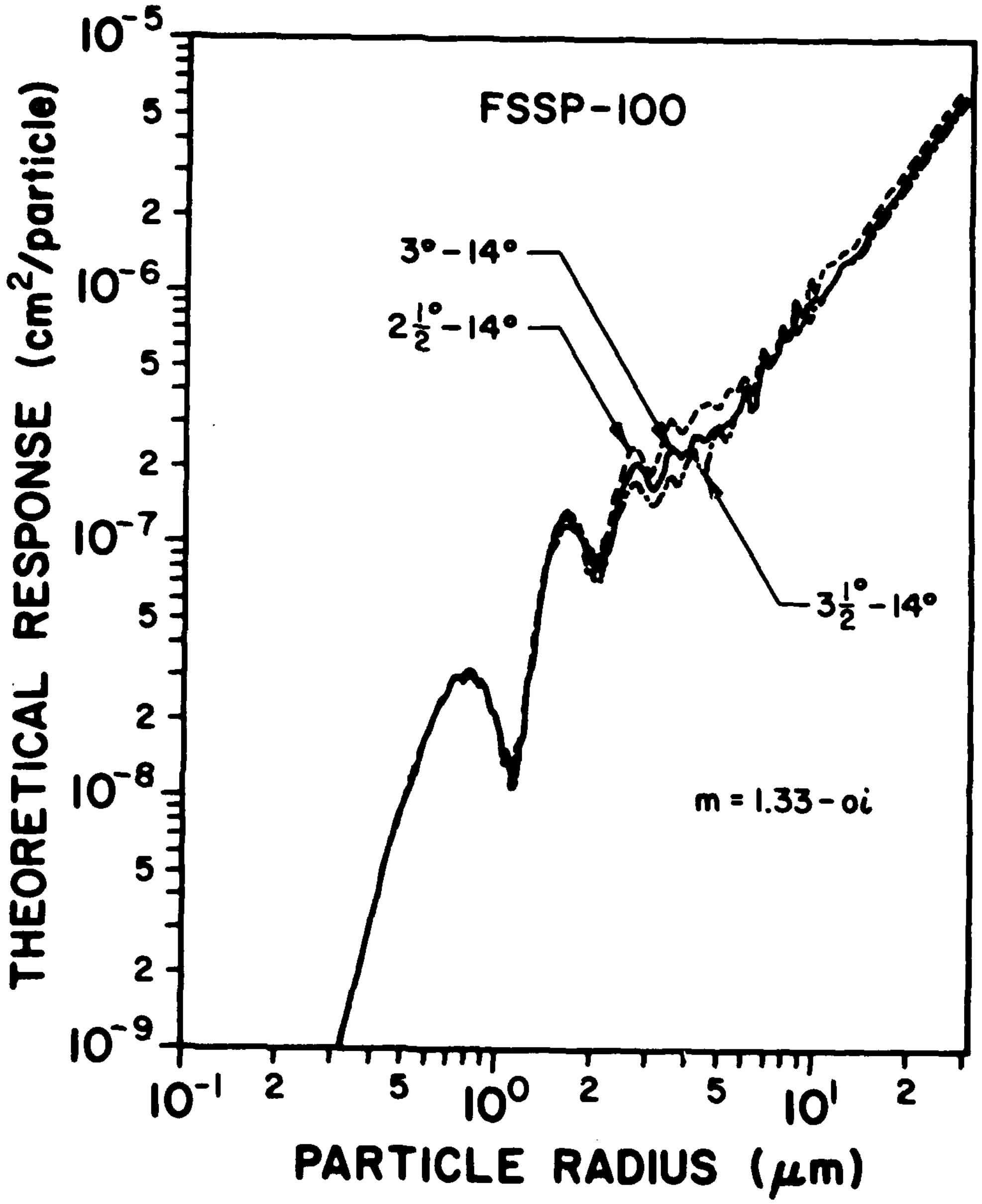

Figure A-2. FSSP response curves for water drops (m = 1.33-0i) for three slightly different solid angles subtended by the light-collecting optics. The solid angles are defined by the angle pairs α - β (see figure A-1).

APPENDIX B

THE MANUFACTURER'S FSSP CALIBRATION

In this appendix we show how the manufacturer's calibration for the FSSP is plotted relative to the theoretical response curve for water in figure 2. The problem is to determine the positions of the instrument discriminator level settings (which are given in the manual in terms of voltages) relative to the theoretical response (in centimeters^2/particle).

Our first step is to determine the values of the discriminator level voltages (DL) for the different ranges of the instrument relative to each other (and worry later about the normalization to theoretical results). For convenience, we choose the top of channel 15, range 0 to be 10 V. The remaining discriminator levels in range 0 can then be taken to first order directly from the manual. To find the voltage levels for the remaining ranges (1, 2, and 3) the gain ratios (GR) for the corresponding preamplifiers must be deduced from the appropriate resistance values given in the manual. Once this gain ratio is found for a particular range, the voltage level for the top of channel 15 for that range can be calculated relative to 10 V (the top of channel 15, range 0). The remaining discriminator levels in that range can then again be determined from the corresponding voltages given in the manual.

A slight modification of this procedure is required because of the negative bias offset voltages (BO) employed in the processing of particle signals. Unfortunately, these bias offset voltages are different for different ranges and for different instruments, and may not be given in the manual. (They can be easily measured, however.) According to the manufacturer (private communication), the effective offset (EO) for each discriminator level is scaled according to the following equation:

$$EO = \left(\frac{10-DL}{10}\right)BO \tag{B-1}$$

where all voltages are in volts.

In order for a signal to achieve a voltage level above a given discriminator level, the amplified pulse due to a particular particle must first overcome this effective bias offset. Thus, the relative discriminator level settings (denoted MC for manufacturer calibration) can be calculated according to the following formula:

$$MC = \frac{DL + \left(\frac{10-DL}{10}\right)BO}{GR} \tag{B-2}$$

In this formula the value of MC is again normalized to 10 V at the top discriminator level of channel 15, range 0. These discriminator level settings (which depend on the preamplifier bias offsets for each range, the discriminator level voltages for each range, and the gain ratios) together with the particle size definitions given in the manual constitute the "manufacturer calibration" and are given in table B-1 for our particular FSSP instrument. It is important to note that there may be differences in bias offsets, discriminator level voltages, and gain ratios for FSSP's of different vintage; calibration of other instruments must necessarily take these differences into account.

The plot of relative discriminator level settings MC (in volts) versus particle size R is fixed by the above procedure. The normalization constant relating the experimental response (in volts) to the theoretically calculated scattering cross section (in centimeters^2) can then be determined by using the experimentally derived response voltages for spherical particles of known size and index of refraction. Using this normalization, the manufacturer's calibration can be plotted relative to the theoretical response curve for the aerosol to be measured.

The normalization constant for our FSSP instrument, providing it is "in calibration" according to the manual, is $C = 2.2 \times 10^6$ V cm^{-2}. As it turned out, our particular FSSP was slightly out of calibration during this study (latex particles peaked in a slightly higher channel than advertised in the manual), necessitating use of a slightly different normalization constant (we used 2.8×10^6 V cm^{-2}). The normalization constant $C = 2.2 \times 10^6$ V cm^{-2} has been used in figures 2, 4, and 7 in order to avoid confusion regarding the application of these results for a particular instrument at a particular time to the more general problem of using the manufacturer's calibration for other FSSP. The response of similar instruments which are, in fact, in calibration according to the PMS instrument manual can be compared with any of the theoretical response curves given in this paper by using the value $C = 2.2 \times 10^6$ V cm^{-2}. (The experimental response measurements shown in figures 1 and 7 are plotted using the normalization constant peculiar to our instrument $C = 2.8 \times 10^6$ V cm^{-2}.)

TABLE B-1. FSSP-100 MANUFACTURER CALIBRATION

	Range 0		Range 1		Range 2		Range 3	
Channel	Radius (μm)	MC* (V)	Radius (μm)	MC (V)	Radius (μm)	MC (V)	Radius (μm)	MC (V)
16	23.5	10.0	16.0	4.562	8.0	1.260	4.0	0.497
15	22.0	8.785	15.0	3.905	7.5	1.146	3.75	0.455
14	20.5	7.651	14.0	3.331	7.0	1.037	3.5	0.414
13	19.0	6.579	13.0	2.829	6.5	0.933	3.25	0.375
12	17.5	5.567	12.0	2.390	6.0	0.833	3.0	0.336
11	16.0	4.620	11.0	2.011	5.5	0.738	2.75	0.298
10	14.5	3.703	10.0	1.688	5.0	0.646	2.5	0.262
9	13.0	2.868	9.0	1.412	4.5	0.559	2.25	0.226
8	11.5	2.223	8.0	1.172	4.0	0.475	2.0	0.192
7	10.0	1.715	7.0	0.960	3.5	0.397	1.75	0.159
6	8.5	1.309	6.0	0.772	3.0	0.322	1.5	0.127
5	7.0	0.978	5.0	0.601	2.5	0.251	1.25	0.0973
4	5.5	0.692	4.0	0.446	2.0	0.184	1.0	0.0690
3	4.0	0.459	3.0	0.305	1.5	0.123	0.75	0.0445
2	2.5	0.263	2.0	0.178	1.0	0.0671	0.5	0.0198
1	1.0	0.0789	1.0	0.0697	0.5	0.0199	0.25	0.0059

*MC denotes the relative discriminator level setting and was calculated according to equation B-2 using discriminator level voltages DL from the instrument manual; gain ratios GR of 1.00, 2.192, 7.935, 20.1 (for ranges 0, 1, 2, 3); and bias offsets BO of 20 mV, 25 mV, 30 mV, 60 mV (for ranges 0, 1, 2, 3).

APPENDIX C

FSSP MEASUREMENTS OF FOG DROP SIZE DISTRIBUTIONS

The data shown in these figures are for 5-min samples taken in Meppen at the dates and times indicated. Comparisons of FSSP fog drop size distributions were obtained in two ways: one using the manufacturer-supplied calibration (dashed curve) and the other using our suggested calibration based on the theoretical response curve of figure 2 (solid curve). The peaks that appear around 0.6μm and 2μm radius in the dashed-curve distributions are believed to be artifacts caused by multivalued response characteristics of the FSSP instrument.

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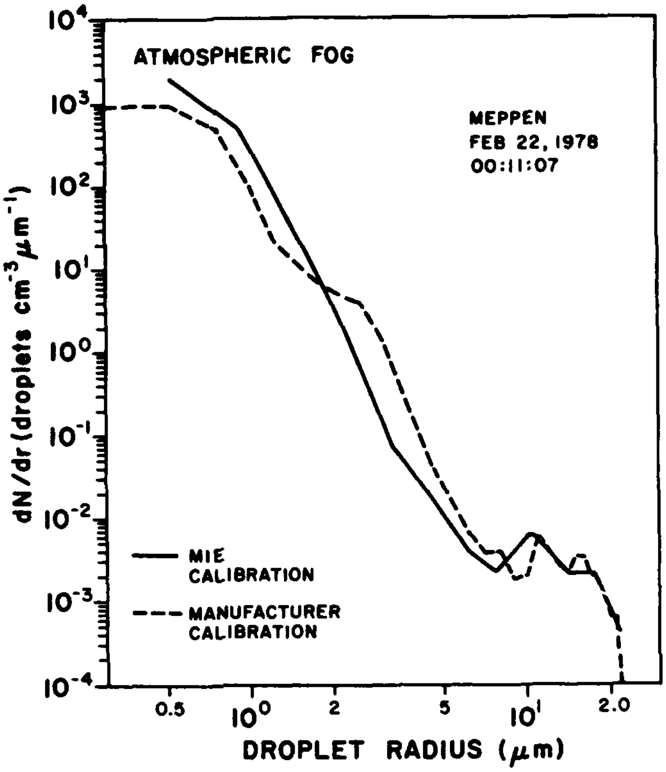


Figure C-1. Comparison for sample taken at 00:11:07, 22 Feb 1978.

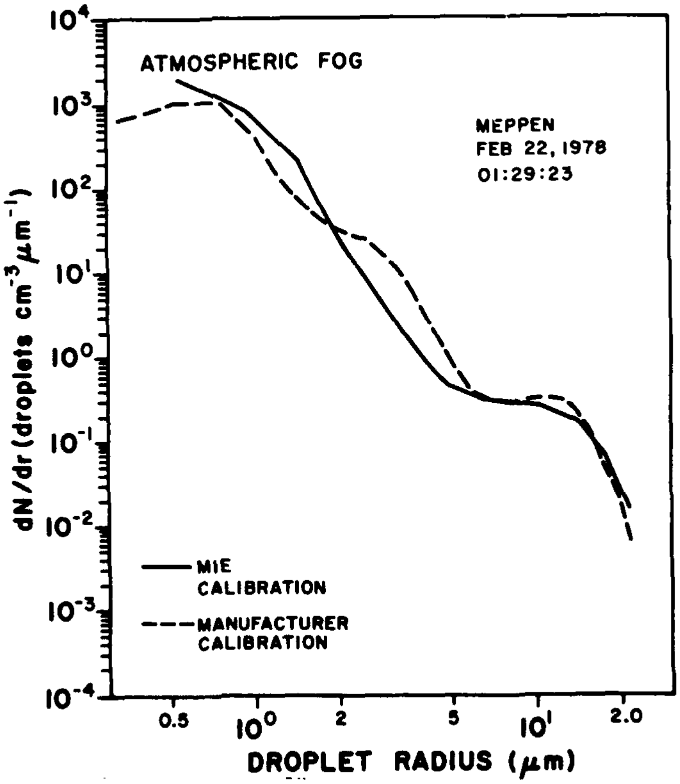


Figure C-2. Comparison for sample taken at 01:29:23, 22 Feb 1978.

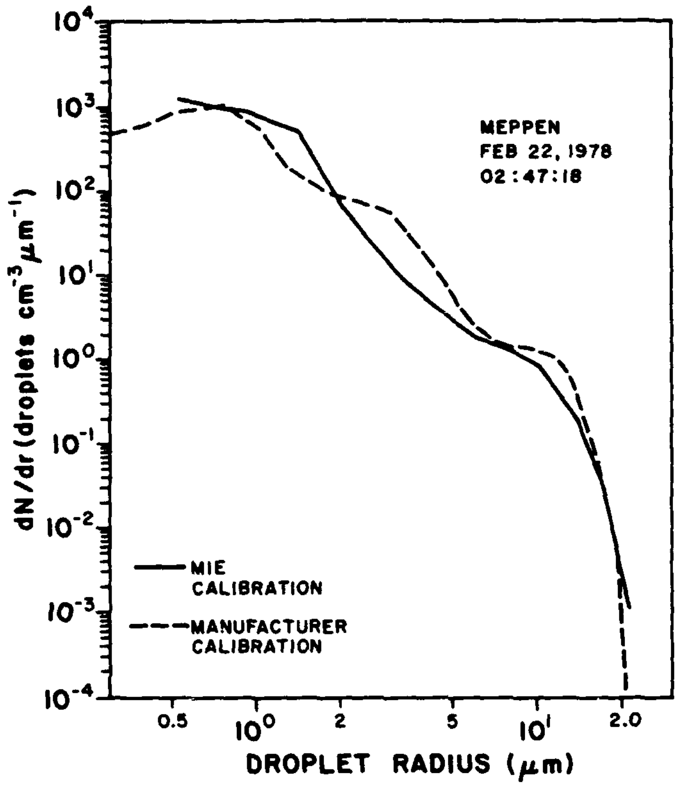


Figure C-3. Comparison for sample taken at 02:47:18, 22 Feb 1978.

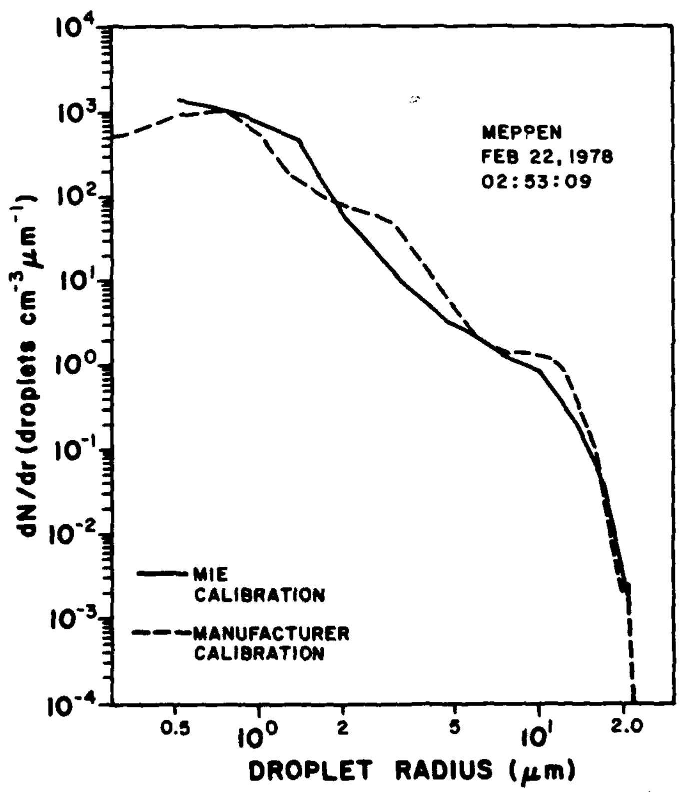
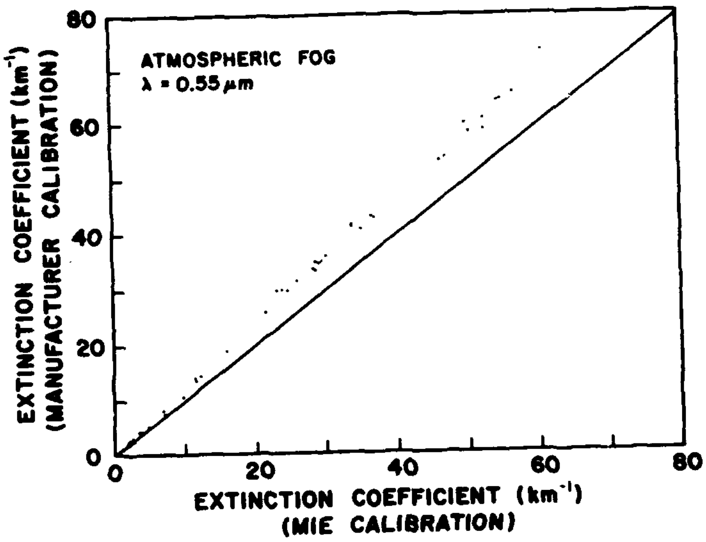


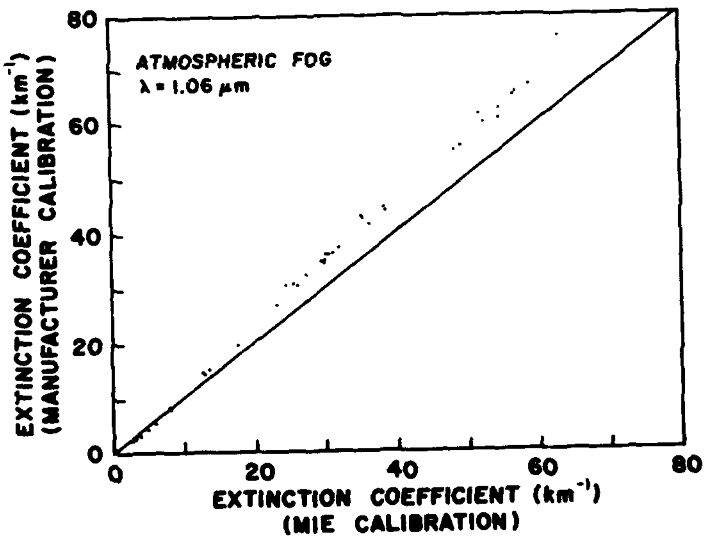
Figure C-4. Comparison for sample taken at 02:53:09, 22 Feb 1978.

APPENDIX D

CALCULATIONS OF EXTINCTION COEFFICIENTS AND LIQUID WATER CONTENTS BASED ON FSSP DATA



(a)



(b)

Figure D-1. Comparison of fog extinction coefficients calculated from FSSP drop size distributions measured during February 1978 in Meppen, Germany. Extinction coefficients are calculated for each case in two ways: one is based on the FSSP manufacturer-supplied calibration and the other is based on our Mie calibration given in table 1. The results show the extinction coefficients derived from the manufacturer calibration are overestimated compared to those based on our Mie calibration, but not by more than 20 percent.

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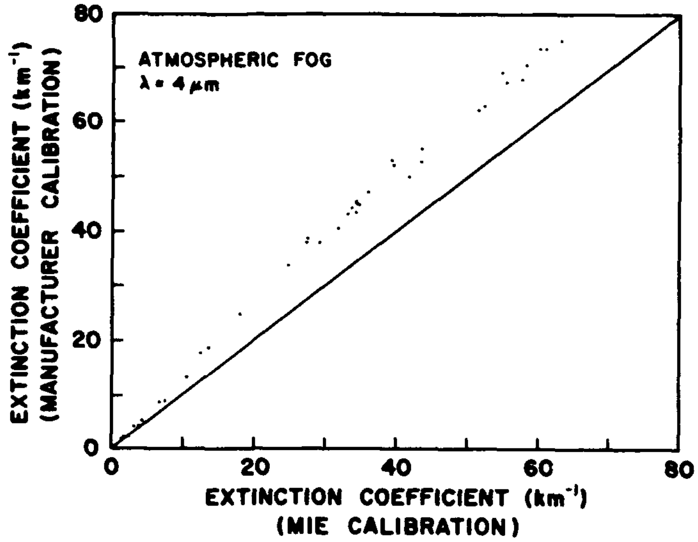
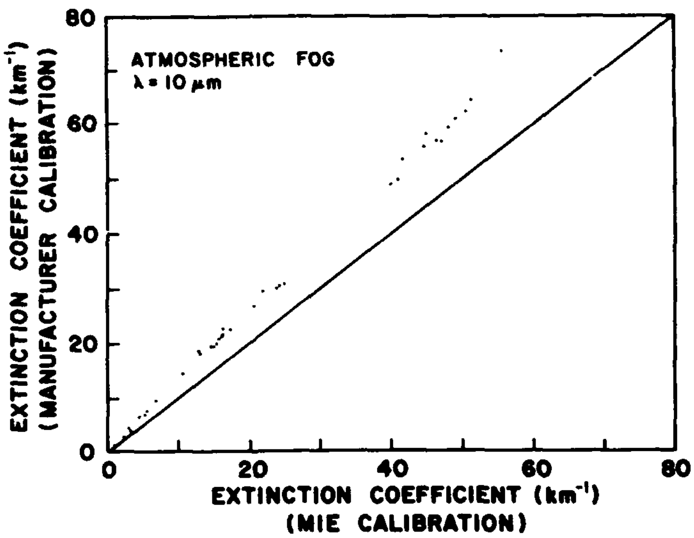


(c)



(d)

Figure D-1. (cont)

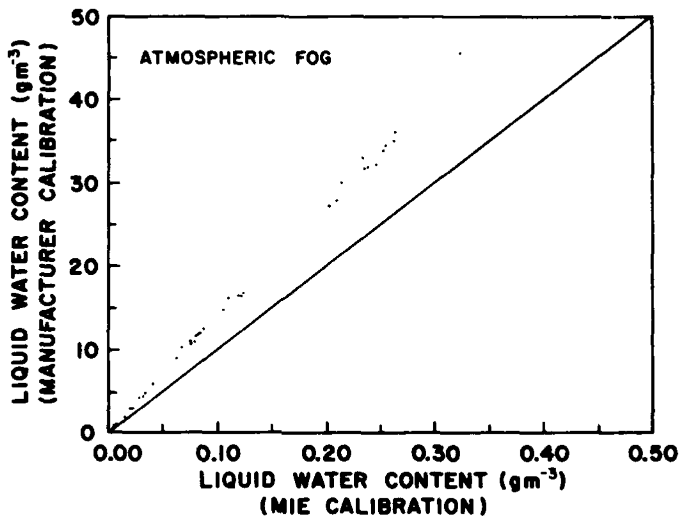


Figure D-2. Comparison of fog liquid water content calculated from FSSP drop size distributions measured during February 1973 in Meppen, Germany. Liquid water content values are calculated in each case two ways: one is based on the FSSP manufacturer-supplied calibration and the other is based on our Mie calibration given in table 1. The results show the liqued water contents derived from the manufacturer calibration are overestimated compared to those based on our Mie calibration, but not by more than 25 percent.

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